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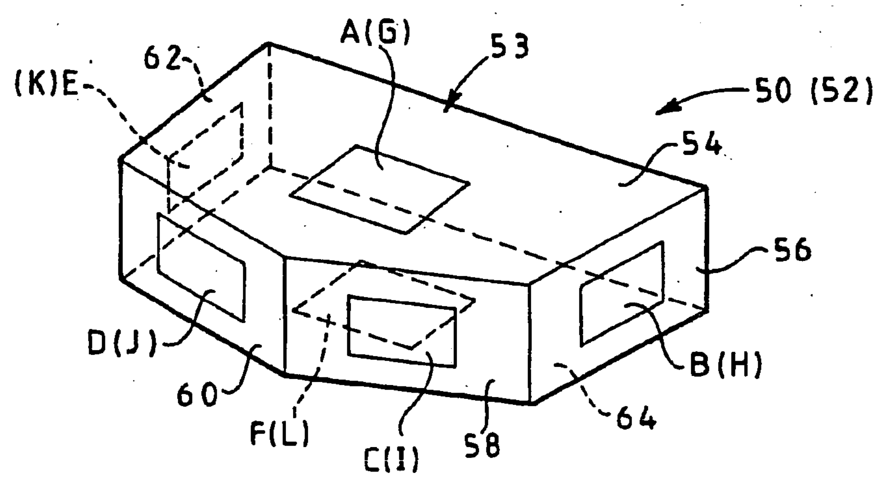

(57) Abstract

A system for determining the position and orientation of a moveable object in space relative to a stationary object has two transmitter units mounted in fixed, spaced relationship on a stationary console and two receiver units mounted on a headset or other moveable object. Each transmitter unit has a triplet of orthogonally arranged LEDs, each of which generates a hemispherical beam of radiation. Each receiver unit has six photodetectors (A-F), each of which has a plane of sensitivity such that the intensity of incident radiation is proportional to the cosine of the angle of incidence of the radiation. The six photodetectors are arranged such that they form four sets of three photodetectors with the photodetectors in each set having their planes of sensitivity arranged orthogonally. Each of the photodetectors generates a direction cosine signal proportional to the intensity of radiation received from each LED. The radiation is pulsed infrared radiation and each LED in turn is pulsed for a pre-set time period. Each photodetector is monitored sequentially during energisation of each LED to obtain a direction cosine signal for the radiation incident at each photodetector in turn from each LED in turn. The resulting signals are processed to determine the position and orientation of the headset in space relative to the LEDs.

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POSITION SENSING USING INTENSITY RATIOS

Field of the Invention

This invention relates to a method and apparatus for determining the relative position and/or orientation of two objects in space and for monitoring changes in said relative position.

Description of the prior art

There are many uses for such a method and apparatus, one of them being to inform a computer about the position and/or orientation of a physical object such as the head and/or other members of a human body in circumstances in which the computer is generating images which take account of movements of the person viewing such images. Applications of immersive virtual reality in the entertainment and other fields are examples of such circumstances. A person experiencing immersive, interactive virtual reality wears a headset by means of which computer generated images are presented to his eyes and accompanying sounds are presented to his ears. These images and sounds are varied by the computer in accordance with movements of the headset wearer's head so that realism is maintained.

Many position sensing proposals have been made in the past but all have drawbacks either of cost of the equipment employed or of complexity of the computations involved which adversely affect the computer response time.

Brief summary of the Invention

The present invention seeks to provide an improved method and apparatus for determining the relative positions and/or orientation of two objects in space.

A system for determining the relative positions of first and second objects in space in the azimuth and vertical directions wherein one of said objects is stationary and the other of said

object is moveable in space, the system comprising:

transmitter means on said first object for generating a radiation beam;

receiver means on said second object for receiving radiation transmitted by said transmitter means;

wherein either:

a) said transmitter means comprises three transmitters in a fixed, spaced relationship to one another for generating respective radiation beams; or

b) said receiver means comprises three receivers in a fixed, spaced relationship to one another for detecting said radiation;

and wherein the or each said receiver has a plane of sensitivity such that the intensity of incident radiation is proportional to the cosine of the angle of incidence of said radiation;

the system further comprising:

means for monitoring said intensity of the radiation incident at the or each said receiver from the or each transmitter and generating a respective direction cosine signal proportional to said intensity;

and micro processor means operable to determine from said signals a pointing vector of said moveable body from said stationary body.

The preferred system according to the present invention uses wide angle beams of infra red (IR) light to measure relative pointing angles. It does not use the intensity of the IR beam but uses the polar distribution of IR energy from each IR transmitter and the relative intensity of triplets of transmitters.

The amount of light emitted from (or received by) the small rectangular surface of an LED (or photo diode) transmitter is almost perfectly circular. Therefore, as the aperture angle increases from 0° to 90° the energy transmitted closely follows a cosine response.

Consider two IR transmitters (or receivers) mounted at 90° to one another with half of the light from each transmitter overlapping the other to form a 90° cone. Within this cone a receiver receives an amount of light from each transmitter. The ratio of these two amounts is related to the angle at which the receiver is situated relative to the transmitters. Since the two LED's produce cosine polar plots and since they are 90° "out of phase" the two dimensional angle at which the receiver is situated is given by the ratio of the amount of light received from the transmitters. Since we are dealing in ratios rather than absolute amplitudes the effects of distance can be ignored.

Now consider three LED's, mounted at 90° to one another. For any line of sight within the octant that can "see" all three transmitters, the ratio of the readings can be used to give the three-dimensional direction cosine of the line of sight. This line of sight region defines an octant of usable field of view.

If two or three receivers are used, mounted orthogonally, the two-dimensional or three-dimensional angle between the boresight of the receivers and the line from the receivers to the transmitters can be measured (Figure 2). By calculation, we therefore have the angle z of the receiver location relative to a base line of the transmitter LEDs. The arrangement is symmetrical, with ratios of LED intensity received at any receiver giving the LED angle x and the ratios of receiver intensity from any LED giving the receiver angle y.

Brief description of the drawings

The present invention is further described hereinafter, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a diagrammatic illustration of the relationship in use between an LED light source and an arrangement of three orthogonal photodetectors;

Figures 2 and 3 are diagrams illustrating the mathematical principles involved;

Figure 4 is a diagrammatic configuration illustrating the principles of a preferred system according to the present invention;

Figure 5 is a diagrammatic representation of a photodetector block for the system of Figure 4;

Figure 6 is a diagrammatic representation in plan of the photodetectors of the system of Figure 4;

Figures 7a and 7b are further diagrammatic configurations illustrating the principles of a preferred system according to the present invention;

Figure 8 is a diagrammatic plan view of a practical system according to the present invention;

Figure 9 is a side elevation of the system of Figure 8;

Figure 10 is a plan view of a transmitter unit for the system of Figure 8;

Figure 11 is a plan view of a photodetector block for the system of Figure 8;

Figure 12 is a perspective view of the photodetector block of Figure 11;

Figure 13 is a diagrammatic plan view illustrating the positions of two of the photodetector blocks of Figure 11 mounted on a head set;

Figure 14 is a pulse timing diagram illustrating the operation of the system of Figure 8;

Figure 15 is a circuit diagram of the transmitter units of the system of Figure 8;

Figure 16 is a block circuit diagram of the control and processing circuitry of the system of Figure 8;

Figures 17 and 18 are pulse timing diagrams illustrating the operation of the circuit of Figure 16;

Figure 19 is a diagram illustrating the manner in which information is processed by the circuit of Figure 16; and

Figure 20 is a diagram illustrating the total azimuth field of view provided by the two photodetector blocks of Figure 13.

Detailed Description

Figure 1 shows a light source LS which conveniently is an LED 80 projecting from a surface 82 such that it diffuses light generally uniformly throughout a hemisphere. This is as distinct from the relatively expensive light sources of some prior art proposals which have required parallel beams of collimated light. Three planar photodetectors, only two of which 84 and 86 are visible in Figure 1, are mounted on orthogonally-related surfaces such as 88 and 90 of a cube 92. The three photodetectors are mounted orthogonally (xyz directions) such that for the purposes of the measurement they may be treated as being at the same point. The position of the light source is determined by measuring the relative intensity of light from the source incident on each of the three detectors. The total intensity of the light at the position of the detectors may be eliminated using simple mathematics. Three direction

cosines may thus be obtained which define the direction of the light source from the position of the detectors. The three photodetectors are connected to a microprocessor and provide it with information as to the relative position in space at any given moment of the light source LS and the cube P according to the intensity of the light from source LS which falls on each of the photodetectors.

References throughout to light sources and to photodetectors are to be taken to include other forms of electromagnetic radiation and to means for detecting the same.

Referring to Figure 2, the intensity I of electromagnetic radiation measured from a constant-intensity source such as the LED 80 is the product of the Intensity I_0 of the radiation falling upon the photodetector 84 or 86 when at right angles to the direction of radiation and the cosine of the angle Θ between the source direction and the normal N to the plane of the detector. As illustrated in Figure 2:

$$I = I_0 \cos\Theta = I_0.N$$

Where:

I_0 = the Intensity of the radiation falling upon the photodetector when the photodetector is at right angles to the direction of radiation,

Θ = angle of incidence of the radiation,

I = the Intensity of the radiation falling upon the photodetector when the photodetector is at the angle Θ to the direction of radiation,

Referring to Figure 3, using two such planar photodetectors 84, 86 at right angles to one another and with the direction to the source of radiation in the plane formed by the detector normals, N_1, N_2, the direction vector T (bearing) of the source can be obtained with respect to the bisector of the angle between the normals N_1, N_2 in the plane, using simple trigonometry.

The value of the intensity can be eliminated from the computation, without affecting its accuracy, using the ratio of the two intensities measured. The use of the ratio also means that the distance between the source LS and detector array P is not a factor in the equation. Thus from Figure 3:

$$\text{ratio } r = \frac{I_0 \cos\Theta_1}{I_0 \cos\Theta_2} = \frac{\cos\Theta_1}{\cos\Theta_2}$$

but if vector T from the target source LS is in the same plane as the normals N_1 & N_2, then:

$$v = 45^\circ - \Theta_1$$

also $$v = -45^\circ + \Theta_2$$

Hence:

$$r = \frac{\cos(45^\circ - v)}{\cos(45^\circ + v)} = \frac{\cos 45^\circ \cos v + \sin 45^\circ \sin v}{\cos 45^\circ \cos v - \sin 45^\circ \sin v} = \frac{1 + \tan v}{1 - \tan v}$$

so

$$\tan v = \frac{r - 1}{r + 1}$$

However, if the direction vector T to the light source LS is not in the same plane as the normals N_1, N_2 of the photodetectors the equations relating the angles do not hold and there is a more complex relationship. Using two of the photodetector pairs with their axes at right angles to each other gives a complex set of relationships between the measured ratios from which it is difficult to disentangle the bearing angles to get a true 3 dimensional bearing vector.

Therefore, instead of using a pair of 2 dimensional devices to try to measure in 3 dimensions the configuration of three detectors in orthogonally-related planes illustrated at P in Figure 1c is provided. The use of this simplifies the measurement and reduces the computation needed to obtain the desired result.

The principle of the 2 dimensional configuration is to get a pair of results at the same time to enable variations in the measured intensity of the light source to be eliminated by taking ratios. If three results are used, however, the ratio method will not work and another way must be found to eliminate the effects of light intensity variation.

The normals of the planes of the three photodetectors 82, 84 are arranged to lie along the principal axes x, y, z of an orthogonal cartesian set. With this arrangement the cosines of the angles which the direction vector I makes with the plane normals is a set of direction cosines so the sum of their squares will be unity. The measurement can therefore be normalised by squaring and adding the measured quantities and then dividing each by the square root of the sum to obtain a set of 3 dimensional direction cosines.

Referring again to Figure 1c, the normals can be considered as a right handed set of cartesian axes taken in the order x, y, z. Each intensity measurement, when taken at the same time, is the product of the light wavefront intensity and the appropriate direction cosine, as follows:

$$r_x = I_0 \cos \Theta_x$$

$$r_y = I_0 \cos \Theta_y$$

$$r_z = I_0 \cos \Theta_z$$

To eliminate the wavefront intensity I_0, the three values are squared and added:

$$r_x^2 + r_y^2 + r_z^2 = I_0^2 (\cos^2 \Theta_x + \cos^2 \Theta_y + \cos^2 \Theta_z)$$

but by definition:

$$\cos^2 \Theta_z + \cos^2 \Theta_y + \cos^2 \Theta_z = 1$$

Hence:

$$r_x^2 + r_y^2 + r_z^2 = I_0^2$$

So the wavefront intensity can be calculated and eliminated from the measurements by division, leaving a set of direction cosines defining a unit vector from the photodetector triad towards the source LS in the given set of orthogonal axes. These axes can be rotated into any other cartesian space as required using general mathematical techniques to give a pointing vector in Virtual Space. Using the vectors to two infra red light sources in the real world enables a head-up vector to be defined and used for a three degrees of freedom tracking system. The head-up vector is normal to the pointing vector and the plane of the pointing vector defined by the two light sources and the photodetector triad.

Referring now to Figures 4 to 6 these represent a system having a single point source of light and two groups of photodetectors.

In Figure 4, the point P represents a source of light, and the points V_1 and V_2 represent the positions of two groups of detectors fixed in a predetermined spaced relationship on a console. The light source at P acts like a point source and emits light with a cosine-like wavefront. Detector groups V_1 and V_2 are sets of orthogonal detectors that are arranged such that the ratio of intensities incident on them will, using simple mathematics, yield the direction of the light source.

Consider the figuration in Figure 4 where the console detectors are deployed at V_1 and V_2, which are known points and pointing directions in the reference frame of the system. What is required for the tracking system is the position of P in the reference frame and the pointing and head-up vectors of the target being tracked.

Finding the point P

1. The bearing of **P** is measured from V_1, giving the direction **P** - V_1.
2. The bearing of **P** is measured from V_2, giving the direction **P** - V_2.

3. The points of closest approach are calculated of the vectors defined by these two bearings. The point **P** is the mid point of the vector joining these two points.

Finding the Pointing and Head-up Vectors

Using the moving frame of reference of the target **P**:-

1. From the target, measure the bearing angles to $\mathbf{V}_1$ and $\mathbf{V}_2$ respectively.
2. Calculate the direction of the vector from the target at right angles to $\mathbf{V}_2 - \mathbf{V}_1$. (Pointing vector)
3. Calculate the normal to the vectors $\mathbf{V}_1 - \mathbf{P}$ and $\mathbf{V}_2 - \mathbf{P}$. (Head-up vector)
4. From these two vectors construct the inverse of the rotation matrix.
5. Invert this matrix to give the rotation matrix, containing the pointing and head-up vectors in the original reference frame.

Theory

Finding the position (bearing) of target P

Measuring the bearings $\mathbf{t}_1$ and $\mathbf{t}_2$ of the target **P** from $\mathbf{V}_1$ and $\mathbf{V}_2$:

Let

$$\mathbf{P}_1 = \mathbf{V}_1 + \mathbf{a}\mathbf{t}_1$$

and

$$\mathbf{P}_2 = \mathbf{V}_2 + \mathbf{b}\mathbf{t}_2$$

The point of nearest approach of these two vectors is calculated as follows:-
The normal to vectors $\mathbf{t}_1$ & $\mathbf{t}_2$

$$\mathbf{n} = \mathbf{t}_1 \times \mathbf{t}_2 \qquad \text{(normalised)}$$

so

$$\mathbf{P} = 0.5\,(\mathbf{P}_1 + \mathbf{P}_2) = \mathbf{V}_1 + \mathbf{a}\mathbf{t}_1 + 0.5l\mathbf{n} = \mathbf{V}_2 + \mathbf{b}\mathbf{t}_2 - 0.5l\mathbf{n}$$

where

$$l = |\mathbf{P}_2 - \mathbf{P}_1|$$

hence

$$\mathbf{V}_2 - \mathbf{V}_1 = a\mathbf{t}_1 - b\mathbf{t}_2 + l\mathbf{n}$$

i.e.
$$\begin{bmatrix} t_{1x} & t_{2x} & n_x \\ t_{1y} & t_{2y} & n_y \\ t_{1z} & t_{2z} & n_z \end{bmatrix} \begin{bmatrix} a \\ -b \\ l \end{bmatrix} = \begin{bmatrix} (V_2 - V_1)_x \\ (V_2 - V_1)_y \\ (V_2 - V_1)_z \end{bmatrix}$$

so
$$\begin{bmatrix} a \\ -b \\ l \end{bmatrix} = \begin{bmatrix} t_{1x} & t_{2x} & n_x \\ t_{1y} & t_{2y} & n_y \\ t_{1z} & t_{2z} & n_z \end{bmatrix}^{-1} \begin{bmatrix} (V_2 - V_1)_x \\ (V_2 - V_1)_y \\ (V_2 - V_1)_z \end{bmatrix}$$

If $\mathbf{V}_2 - \mathbf{V}_1$ is lined up with the x-axis as shown in Figure 1 then $(V_2 - V_1)_y$ and $(V_2 - V_1)_z$ are both zero.

Angular Degrees of Freedom

To determine the orientation of the headset, the direction from the source to each of the two detector groups are measured. Using these directions, a vector from the source which is perpendicular to the line connecting the two detector arrangements is calculated. The direction of the vector normal to the plane defined by the source and the detectors is calculated. A third vector, normal to the previous two vectors is also calculated. These three vectors define a set of orthogonal axes which characterise the orientation of the headset.

The mathematical description of the above calculation is as follows:-

Measure the bearing angles of $\mathbf{V}_1$ and $\mathbf{V}_2$ from $\mathbf{P}$ in the moving coordinate system, getting

unit vectors $\mathbf{g}_1$ and $\mathbf{g}_2$.

Let the head-up vector be **h**, where:-

$$\mathbf{h} = \mathbf{g}_1 \times \mathbf{g}_2 \quad \text{(normalised)}$$

and the pointing vector be **p**, where:-

$$\mathbf{p} = A\mathbf{g}_1 + B\mathbf{g}_2$$

A and B are obtained from the relationship calculated from the base position of the pointing vector and the two vectors $\mathbf{P} - \mathbf{V}_1$ and $\mathbf{P} - \mathbf{V}_2$, as follows:-

Let $\mathbf{g}'_1 = \mathbf{V}_1 - \mathbf{P}$ (normalised)

and $\mathbf{g}'_2 = \mathbf{V}_2 - \mathbf{P}$ (normalised)

and $\mathbf{O} = \mathbf{P} - \mathrm{P}_y$

then $\mathbf{O} - \mathbf{P} = \mathbf{p}$ (normalised)

so $\mathbf{p}' = A\mathbf{g}'_1 + B\mathbf{g}'_2$

so $A = -B(g'_{2x}/g'_{1x})$ or $B = -A(g'_{1x}/g'_{2x})$

and $B = -p'_y.g'_{1x}/(-g'_{2x}.g'_{1y} + g'_{2y}.g'_{1x})$ or $A = -p'_y.g'_{2x}/(g'_{2x}.g'_{1y} - g'_{2y}.g'_{1x})$

Then

$$\mathbf{b} = \mathbf{p} \times \mathbf{h}$$

Then the rotation matrix which is used to rotate the moving axes into alignment with the fixed axes is constructed by using the elements of **b**, **p** (pointing vector) and **h** (head-up vector) taken in this order to make the rows of the matrix.

$$\begin{bmatrix} b_x & b_y & b_z \\ p_x & p_y & p_z \\ h_x & h_y & h_z \end{bmatrix}$$

This matrix must be the inverse of that which rotates the axes of the fixed coordinate system into that of the headset, which is therefore:-

$$[r] = \begin{bmatrix} b_x & p_x & h_x \\ b_y & p_y & h_y \\ b_z & p_z & h_z \end{bmatrix}$$

The pointing and head-up vectors are calculated with respect to the plane defined by **P**, $\mathbf{V_1}$ and $\mathbf{V_2}$. In practice, this may not be the azimuthal plane, but have an offset angle ϕ defined by the headset design, which will necessitate a rotation of the pointing and head-up vectors into the world coordinate system.

Coordinate Systems

The console devices from which the bearings to **P** are measured each has its own coordinate system. The relationships of these coordinate systems to the viewer world coordinate systems are fixed by the placement of the console units on their mat. A rotation matrix is made for each point to rotate the local axes into line with the world system.

The axes are defined as follows:-
for $\mathbf{V_1}$

$$[r_1] = \begin{bmatrix} -sA_1 & -cA_1 & 0 \\ cE_1.cA_1 & -cE_1.sA_1 & sE_1 \\ -sE_1.cA_1 & sE_1.sA_1 & cE_1 \end{bmatrix} \quad \text{see Figure 7a}$$

for $\mathbf{V_2}$

$$[r_2] = \begin{bmatrix} -sA_2 & -cA_2 & 0 \\ cE_2.cA_2 & -cE_2.sA_2 & sE_2 \\ -sE_2.cA_2 & sE_2.sA_2 & cE_2 \end{bmatrix} \quad \text{see Figure 7b}$$

Where s and c are sine and cosine respectively, and E and A are elevation and azimuth angles

The negative signs for A_1 and A_2 have been taken into account in the matrices.

Calculations from Measurements

From $\mathbf{V_1}$ and $\mathbf{V_2}$, the console devices, pairs of bearing vectors $\mathbf{t_1}$ and $\mathbf{t_2}$, right and left are measured and from the detector in the moving target, two vectors $\mathbf{g_1}$ and $\mathbf{g_2}$ are measured.

The following calculations are made-

Add $\mathbf{t_1}$ right and left together and normalise to get $\mathbf{t_1}'$.
Add $\mathbf{t_2}$ right and left together and normalise to get $\mathbf{t_2}'$.

The Azimuth and Elevation angles of the boresight at $\mathbf{V_1}$ are used to get the rotation matrix $[\mathbf{r_1}]$ and similarly for V_2.

Calculate $[\mathbf{r_1}].\mathbf{t_1}'$ and $[\mathbf{r_2}].\mathbf{t_2}'$ to get $\mathbf{t_1}$ and $\mathbf{t_2}$ respectively.

Then

$$\mathbf{n} = \mathbf{t_1} \times \mathbf{t_2} \qquad \text{(normalised)}$$

and

$$D = t_{1x}.(t_{2y}.n_z - t_{2z}.n_y) + t_{2x}.(t_{1z}.n_y - t_{1y}.n_z) + n_x.(t_{1y}.t_{2z} - t_{1z}.t_{2y})$$

so

$$a = (1/D).(t_{2y}.n_z - t_{2z}.n_y).(V_2 - V_1)_x$$
$$l = (1/D).(t_{1x}.t_{2y} - t_{1y}.t_{2x}).(V_2 - V_1)_x$$

giving

$$\mathbf{P} = \mathbf{V_1} + a.\mathbf{t_1} + 0.5l.\mathbf{n}$$

Pointing Angles

Let $g'_1 = V_1 - P$ (normalised)

and $g'_2 = V_2 - P$ (normalised)

calculate $A = -B(g'_{2x}/g'_{1x})$ or $B = -A(g'_{1x}/g'_{2x})$

and $B = -p'_y.g'_{1x}/(-g'_{2x}.g'_{1y} + g'_{2y}.g'_{1x})$ or $A = -p'_y.g'_{2x}/(g'_{2x}.g'_{1y} - g'_{2y}.g'_{1x})$

$\mathbf{g}_1$ and $\mathbf{g}_2$ are the measured unit vectors from **P** to $\mathbf{V}_1$ and $\mathbf{V}_2$ respectively

so

$\mathbf{p} = A\mathbf{g}_1 + B\mathbf{g}_2$

and $\mathbf{h} = \mathbf{g}_1 \times \mathbf{g}_2$ (normalised)

$\mathbf{b} = \mathbf{p} \times \mathbf{h}$

Four sets of three orthogonal detectors are used at each of the points V_1 and V_2. The detectors are arranged on a D-shaped block as depicted schematically in Figure 5 and described in more detail below. Each of the faces of the D-shaped block accommodates a single detector . In Figure 5, detectors 5 & 6, and 4 & 7 are orthogonal pairs. These pairs may be used in combination with either of detectors 0 or 1 to form four sets of three orthogonal detectors.

Each of the four sets of detectors at points V_1 and V_2 measures in turn the intensity of the point light source. The orthogonal set of detectors at each of V_1 and V_2 that returns the greatest total signal is used to determine the vectors which define the position of the source.

Detector pairs 5 & 6 and 4 & 7 are positioned at an angle of ten degrees relative to each other. Thus, octants described by these pairs when used in connection with detectors 0 and 1 overlap by 10 degrees. When the light source is in the field described by this overlap, its position is determined by both sets of detectors. The position of the source as measured using both sets of detectors is compared. This removes the possibility of a discontinuity in the calculated position of the source upon transition between octants. The 10 degree angle

between the detector pairs also confers a second important benefit. Measurement of a directional cosine by any given detector will become inaccurate when the angle subtended by the source relative to the detector normal approaches ninety degrees. This is because the intensity of light incident on the detector is very low. The ten degree angle between detectors 4 and 6 reduces the maximum angle subtended by the light source to either of the detectors to 85°.

Detectors 0 and 1 face in opposite directions. Therefore, the fields that they describe in combination with the other detectoıs of the group do not overlap. A possible discontinuity in the determination of the position of the source as it crosses between the two fields is removed by orienting the two detector groups as shown in Figure 6. The D-shaped detector groups are arranged so that detectors 0 and 1 are vertical. There is an angle of 135° between the bases of the detector groups. In this formation, there is considerable overlap between the fields covered by the two detector groups. In particular, when the detectors are mounted on a headset, discontinuities will be avoided when the source is in the region directly in front of the headset. This is important as the source will be in this position for the majority of the time over which the headset is used.

A person wearing the headset is unlikely to be on a plan level with a console containing the light source. Accordingly, the two D-shaped detector blocks are angled downwards towards the source at 45°.

The theory of operation of the source and headset requires a single point source of light. In practice however, to provide a sufficiently strong optical intensity over the required area, three wide angle light emitting diode sources are used. The diodes are arranged so that they emit light that appears to come from a common source.

Non-Orthogonal Detectors

The generation of three direction cosines of the bearing vector using three detectors depends, in the above derivation, on the three detectors being mutually at right angles to make an

orthogonal set. This constraint can be removed by using a set of modification matrices, one for each set of three non-orthogonal detector readings taken.

The modification matrix is derived as follows:-

Let r_1, r_2 and r_3 be the three readings taken

then $r_1 = I_0.\cos\Theta_1$ where I_0 is the IR light amplitude and Θ_1 the angle between the bearing vector and the detector unit normal **n**.

Let the unit vector in the bearing direction be **v**

then $r_1 = I_0.\mathbf{v}.\mathbf{n}_1$

similarly $r_2 = I_0.\mathbf{v}.\mathbf{n}_2$ and $r_3 = I_0.\mathbf{v}.\mathbf{n}_3$

i.e.

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix} = \begin{bmatrix} v_x.n_{1x} + v_y.n_{1y} + v_z.n_{1z} \\ v_x.n_{2x} + v_y.n_{2y} + v_z.n_{2z} \\ v_x.n_{3x} + v_y.n_{3y} + v_z.n_{3z} \end{bmatrix} I_0$$

so

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix} = \begin{bmatrix} n_{1x} + n_{1y} + n_{1z} \\ n_{2x} + n_{2y} + n_{2z} \\ n_{3x} + n_{3y} + n_{3z} \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} I_0$$

i.e. $\mathbf{R} = [\mathbf{N}].\mathbf{v}.\mathbf{I}_0$

so $[\mathbf{N}]^{-1}.\mathbf{R} = \mathbf{v}.\mathbf{I}_0$

normalising $\mathbf{v}.\mathbf{I}_0$ gives **v**.

Clearly if the detector normals are orthogonal [N] is a rotation matrix and if they are lined up with the world axes, then [N] = [I] the unity matrix.

Example of a Set of Non-Orthogonal Detectors

Consider a regular dodecahedron. This solid has twelve faces, each of which is a regular pentagon. If each face contains a detector, then each set of three detectors grouped around a vertex can be used to get a bearing of a target anywhere in the surrounding space.

There are twenty vertices so it would be necessary to pre-compute the modification matrices for each set of detectors grouped around a vertex, giving twenty matrices at maximum. For a more limited coverage, this number could be reduced.

For instance, if one face were to be used to mount the device on the target, only eleven detectors would be needed and fifteen modification matrices.

The angles between pairs of adjacent normals are 64°, giving a good overlap to prevent the necessity for measuring small signals, and giving good noise immunity.

Refering now to Figure 8 this is a plan view of part of the preferred system having two transmitter units 10, 12 and a receiver station in the form of a receiver headset 40 which, in use, is worn by a user of the system and which carries two receiver units 50, 52. Figure 9 is a side elevation of the system of Figure 8 showing the transmitter units mounted on a console 13. It will be appreciated that whilst a headset is referred to, the receiver station may be any movable object, e.g. a joystick. In addition, although the receiver units are described as being on the movable object and the transmitter units stationary, this may be reversed with the transmitter units on the movable object and the receiver units stationary.

Referring firstly to the transmitter units 10, 12 these are arranged at the same horizontal level on the console 13 along an arbitrary base line 14 so that when the user is standing or sitting in the normal or base position of use 16 the transmitter units are below and approximately equi-distant from the centre of the headset 40.

Each transmitter unit comprises a 3-sided pyramid 11 (Figure 10) in which each side face 18,

20, 22 of the pyramid is at right angles to each adjacent side. In effect, each pyramid is the corner of a cube.

Figure 10 is a plan view of one transmitter unit 10 (the other transmitter unit being identical) showing the three side faces 18, 20, 22 of the pyramid. Each side face carries a transmitter 24, 26, 28 in the form of a light emitting diode (LED) arranged such that its "cone" of transmission has an axis which is at right angles to the plane of the associated side face and to the base line 30, 32, 34 of the associated side face. The angles of the apexes of the three side faces are identical and typically 90° such that the "cones" of light from the LED's overlap. The axes of transmission intersect. It will be appreciated, of course, that although the LEDs are described and shown here as being arranged orthogonally, this is not essential. The LEDs are preferably infra red LEDs.

The LEDs 24, 26, 28 are positioned on the pyramid side faces and/or the angles of the pyramid side faces are such that for three degrees of freedom at least one receiver unit 50, 52 on the headset always "sees" at least one LED. For six degrees of freedom each receiver "sees" three LEDs. Movement of the headset 40 when worn by a user is, of course, physically constrained within certain.

It will be appreciated, therefore, that the axis of each pyramid 11 (the perpendicular from the pyramid base through the apex) extends, ideally, through the centre of the headset 40 when the latter is in its base position.

Figure 11 is a plan view of one of the receiver units 50 and Figure 12 is a perspective view of the receiver unit of Figure 11. The two receiver units 50, 52 are identical. Each receiver unit has a body 53 in the form of a block having plain parallel side faces 54, 64, opposing upper and lower faces 56, 62 and front faces 58, 60. Each of these faces is generally planar and parallel to a vertical axis passing normal to the faces 54 and 64. Faces 56 and 62 are inclined inwardly towards one another by an angle α of 5° whilst the faces 58 and 60 form an angle β of 135°.

Each of the faces 54 to 64 has a respective planar photodetector A to F for detecting infrared light emitted by the LEDs on each of the transmitter units 10, 12. For ease of reference the corresponding photodetector references for the receiver unit 52 are shown in brackets in Figures 11 and 12 against the corresponding photodetector references of the receiver unit 50. The photodetectors generate output signals in response to detection of the infra red light and these output signals are processed by a processor circuit 100 connected both to the LED's and to the photodetectors. The angles of the faces 54 to 64 as mentioned above are such that face 60 is at right angles to face 56 and face 58 is at right angles to face 62. The result of this is that the six photodetectors A to F form four sets or triplets of orthogonal detectors. As seen in Figures 11 and 12 these four triplets are ABD, ACE, FBD and FCE. As is mentioned above, two such receiver units 50, 52 are mounted on the headset 40 and as indicated in Figures 11 and 12 the receiver unit 52 has six photo receivers G to L. These form three sets or triplets of orthogonal detectors GHJ, GIK, LHJ and LIK. Because, in use, the headset is higher than the transmitter units 10, 12 the receiver units 50, 52 are angled downwardly by typically 45°, towards the console 13 on which the transmitter units are mounted, although the angle may be varied depending on the distance of the user from the transmitter units 10, 12.

Each receiver unit 50, 52 is positioned on the headset 40 with the planes of the side faces 54, 64 generally vertical. In addition, each receiver unit 50,52 is positioned on the headset 40 so that it faces forward at an azimuth angle of 22.5° to the forward line of sight of the user when the latter is looking in a direction forward at 90° to the base line 14 of the transmitters 10,12, as a result of which the normals to the side faces 54, 64 of the two receiver units 50, 52 subtend an angle of 135°, as shown in Figure 13.

In use, each LED of the transmitter units 10, 12 is pulsed in sequence, each LED transmitting a burst of eight pulses of infra red light at 125KHz. Each pulse of the burst is therefore 4 μsecs with a pulse spacing of 4 μsecs.

Figure 14 is a timing diagram showing the timing of the pulse bursts, L1 being the transmission for the first LED in the first transmitter unit 10 or 12, whichever is activated

first, and L6 being for the sixth LED in the other transmitter unit. A "dummy" transmission L0, in which none of the LEDs is activated precedes L1 and a further "dummy" transmission L7 follows the pulse burst L6. Each transmission and dummy transmission occupies 64 μsecs, the total transmission time for one cycle thus being 512 μsecs.

The purpose of the dummy transmission L0 is to null out any DC offset in the signals for subsequent processing of the signals by the processor circuit 100 whilst the dummy transmission L7 is to allow switching between the photodetectors A to F as discussed below without the switching interfering with the signal processing.

In the receiver units 50, 52 each photodetector A to L is, in turn, switched on for one complete transmission cycle L0 to L6 of the transmitter units 10, 12. Thus, whilst each photodetector A to L in turn is ON, all of the remaining photodetectors are OFF.

Figure 15 is a circuit diagram of the two receiver units 50, 52 and Figure 16 shows a block circuit diagram of the signal processing circuit 100.

Referring firstly to Figure 15, each photodetector A to L of each receiver unit 50, 52 is shown controlled by a switch in the form of a field effect transistor (FET) 102. The photodetectors A to F are connected in parallel with one another, as are the photodetectors G to L. The photodetectors are conveniently photodiodes.

Figure 17 shows a timing diagram for activation of each of the photodetectors A to L. As can be seen, for example, the switch 102 for the photodetector A is on for the transmission cycle L0 to L6 and is switched OFF during the dummy transmission period L7. During this time all of the other switches 102 for the photodetectors of both receiver units are OFF. Whilst the switch 102 for photodetector A is switched OFF during the dummy transmission period L7, the switch 102 for photodetector B is switched ON during this dummy transmission period and is then switched OFF during the next following dummy transmission period L7. The other photodetectors C to L are each switched ON and then OFF in turn. It will be appreciated, therefore, that each photodetector A to L generates an output signal, for each

transmission period L1 to L6, for the train of pulses received from each transmitter LED. Considering photodetector A, for example, this generates a sine wave signal S_A (Figure 18) of the same frequency as the pulses transmitted by the transmitters 24, 26, 28 i.e. 125KHz. The amplitude of the sine wave signal S_A generated by the photodetector A in response to receipt of each of the pulse trains L1 to L6 depends on the position and orientation of the photodetector A in space relative to the particular transmitter LED. If, for example, photodetector A is oriented such that it cannot "see" the transmitter LED transmitting the pulse train L3 then no output signal is generated. If, on the other hand, the photodetector A lies at right angles to the axis of the transmission cone of the LED transmitting the pulse train L3 then its output signal amplitude depends simply on the linear distance between the photodetector A and the relevant LED, the intensity of the received infrared light varying in accordance with the inverse square law.

Continuing to look at photodetector A, Figure 18 shows the typical signal S_A generated in the photodetector A, in response to detection of the pulses transmitted by the transmitter units 10, 12. As can be seen, the amplitude of the sign wave signal S_A generated by the photodetector A varies in dependence on the intensity at the optical detector A of the pulse train signal L1 to L6 transmitted by the relevant transmitter LED of the transmitter units 10, 12. Each of the photodetectors B to L produces a similar signal to signal S_A but only the beginning of signal S_B (from photodetector B) is shown for clarity in Figure 18.

Each of the signals from the photodetectors A to L is passed through a buffer amplifier 104, 106 (one for each receiver unit 50, 52) and the outputs of the two buffer amplifiers 104, 106 are passed through a multiplexer 108 to an automatic gain control (AGC) circuit 110. The multiplexer circuit 108 is used to switch the AGC circuit 110 between the buffer amplifiers 104, 106 to receive the successive signals from the photodetectors A to L. The gain of the AGC circuit 110 is adjusted in accordance with the intensity of the received signal to ensure that a reasonable signal level is provided at its output.

The signals from the AGC circuit 110 are then passed through a high pass filter 112 which has a low frequency cutoff at about 10KHz. This removes any DC signals, 50Hz and 100Hz

interference signals which may be caused by daylight or artificial light. Figure 18 shows the output signal S_{HP} generated at the output of the high pass filter 112 by the signal S_A from photodetector A.

The output S_{HP} of the high pass filter is passed through a rectifier circuit 114 to give a rectified signal S_R and then through an integrator/inverter circuit 116. Because the integrator/inverter circuit 116 adds the pulses from the rectifier, any random noise in the signal is cancelled out. The integrator/inverter circuit 116 ramps each series of pulses L1 to L6 down to a level which depends on the amplitude of the pulses of signal S_R from the rectifier circuit 114. The ramped signal S_I is then held at its ramped level for a set period before being reset to 0 to begin integration of the next series of pulses from the rectifier circuit 114. The first pulse of each sequence of eight pulses L1 to L6 is not used to contribute to the signal amplitude but is used to switch the multiplexer between the amplifiers 104, 106 and to reset the integrator/inverter circuit 116.

The output of the integrator/inverter circuit 116 is then applied to a buffer circuit 118 which comprises an inverter and level shift. This shifts the level of the input signal by -5v, converts the signal to a positive going signal S_P from -5v to +5v and applies this signal to an analogue to digital converter (ADC) 120.

The last half pulse of each sequence of eight pulses of the transmissions L1 to L6 is used to hold the amplitude of the signal from the output signal from the integrator/inverter circuit 116 for sampling by the ADC 120. As a result, only 6.5 pulses from each series of eight pulses is actually used in the subsequent processing. The ADC 120 samples the output S_P of the buffer amplifier 118 only during the "hold" period of each ramped output signal, i.e. it samples the signal once every 64 micro seconds and provides a 14 bit output signal which represents the amplitude level of the sampled hold signal. It will be appreciated, therefore, that for the periods L0 to L6 of each transmission cycle the ADC 120 provides a first 14 bit signal representative of the background noise present during period L0 and six, 14 bit signals representative of the amplitude of the infra red light signals received by the photodetector which is ON during the periods L1 to L6 of that transmission cycle. With all twelve

photodetectors A to L this gives a total of eighty four 14 bit signals for one complete monitoring cycle.

The signals from the ADC 120 are passed to a field programmable gate array 122 and a micro processor 124 which then processes the information.

The first step in processing the signals from the ADC 120 is to subtract the signal L0 from each of the signals L1 to L6 of the transmission cycle. This removes any DC level from the signals to be processed.

The further processing is described with reference to Figure 19 which is a chart of the 14 bit numbers for each combination of the photodetectors A to L and transmitters L1 to L6. For example, the rectangle identified by the photodetector C and the transmission L2 is the 14 bit digit representing the intensity of the light received by the photodetector C from the transmission L2. Similarly, the rectangle HL1 is the 14 bit digit representing the intensity of the optical signal received by the photodetector H from the transmission L1. It will be recalled that the optical detectors are arranged in triplets with the optical detectors A to F arranged in four triplets ABD, ACE, FBD and FDE. Although the transmission L1 occurs only once for the photodetectors A to F over a single transmission cycle, in order to facilitate the explanation the response of the four triplets of the photodetectors A to F to the transmission L1 are shown in separate columns with the four triplet groups being identified respectively as a, b, c and d. The triplets for transmission L1 are shown grouped by shaded cells in vertical columns. Thus, the triplet ABD is identified in the first column, and so on. The same applies for transmitters L2 and L3. For example, $AL1_a$ refers to the 14 bit digit representing the intensity of the light received by the photodetector A from the transmission L2 when it is processed as a signal from the triplet ABD. $AL1_b$ refers to the same 14 bit digit when it is processed as a signal from the triplet ACE. This applies also to the transmissions L2 to L6 and photodetectors G to L.

The first upper left hand quadrant (photodetectors A to F and transmissions L1 to L3) of Figure 19 represents the signals received by the right hand receiver unit 50 from the three

LEDs of the right transmitter unit 10. The upper right hand quadrant represents the signals received by the right hand receiver unit 50 from the left hand transmitter unit 12, the lower right quadrant represents the signals received by the left hand receiver unit 52 from the left hand transmitter unit 12 and the lower left quadrant represents the signals received by the left hand receiver unit 52 from the right hand transmitter unit 10. Since the processing of the signals in each quadrant is the same, only the processing of the signals for the upper left quadrant, as shown, is described.

Firstly, the micro processor 124 looks at the signals from each photodetector of a triplet, for each of the transmissions L1 to L3. If the signal from any one of the photodetectors of a triplet is 0 or less than a preset threshold level for a transmission then all of the signals of that triplet for that transmission are ignored. For example, if each of the photodetectors A, B and D of the triplet ABD provides a signal for each transmission L1 and L2 which is above the present threshold level but photodetector A does not provide a signal above this threshold for transmission L3, then not only is the signal from photodetector A ignored for transmission L3 but the signals from photodetectors B and D for transmission L3 are also ignored. Only those signals from the triplet ABD for transmissions L1 and L2 are taken for further processing.

If the 14 bit digit for each photodetector is represented by N_n where n is the cell reference then the amplitude of the signal received by photodetector C from transmitter L1 is represented by N_{CL1}.

For simplicity, if we assume that each 14 bit digit which represents a signal level below the preset threshold is 0, if $N_{AL1} = 0$ (i.e. the intensity of the light received by the photodetector A from the transmitter L1 is below the preset threshold level) then the signals received by photodetectors B and D in the triplet ABD and the signals received by photodetectors C and E in the triplet ACE from the transmission L1 are ignored. Thus, signals N_{BaL1}, N_{DaL1}, N_{CbL1} and N_{EbL1} are all ignored since the signal N_{AL1} for each of the triplets ABD and ACE is 0. This process is repeated for transmissions L2 and L3. However, it should be appreciated that the signal received by photodetector A from transmission L2 may well be above the threshold

level in which case N_{AL2} will not be 0. Therefore, the signals from, for example, the photodetectors of the triplet ABD for the transmission L2 are not ignored (unless either of the signals received by the photodetectors B and D of this triplet ABD from transmission L2 is 0 i.e. N_{BL2} or N_{DL2} is 0. If we take the example where N_{AL1} and N_{BL2} are both below the threshold this leaves the signals from the following triplets to be processed:

For transmission L1: BDF and CDF.

For transmission L2: ABD, ACE and CDF

For transmission L3: ABD, ACE, BDF and CDF.

For transmission L1 the signals from the triplets BDF and CDF are added i.e. the numbers N_{BcL1}, N_{DcL1}, N_{FcL1}, N_{CdL1}, N_{DdL1} and N_{FdL1} are added to give a first summed signal ΣL1.

This process is repeated for the numbers for transmissions L2 and L3 to provide further summed signals ΣL2 and ΣL3. The largest of these three signals ΣL1, ΣL2 and ΣL3 indicates which of the transmissions L1 to L3 of the right hand transmitter unit 10 provides the greatest intensity signal at the photodetectors A to F of the right hand receiver unit 50. If, for example, ΣL2 is the largest of these three signals then the signals for the photodetectors of each available triplet for the transmission L2 are summed. Thus for the triplet ABD the signals N_{AaL2}, N_{BaL2} and N_{DaL2} are summed to provide a signal Σ_{L2}ABD. Equally, summed signals Σ_{L2}ACE and Σ_{L2}CDF are also obtained for the transmission L2. The largest of these three signals determines which of the triplets is used in the calculations to determine the orientation and position of the headset relative to the transmitter units 10, 12. Having chosen the largest signal, eg Σ_{L2}ACE then the three ratios of each of the signals received by the photodetectors A, C and E to ΣACE enable the calculation of the pointing angle (or "directional" vector) from the right hand receiver unit 50 to the right hand transmitter unit 10.

The same calculations are performed for the remaining three quadrants of Figure 19 to give

the "directional" vectors from the right hand receiver unit 50 to the left hand transmitter unit 12 and also from the left hand receiver unit 52 to both the right hand and left hand transmitter units 10, 12. The signal ratios thus obtained enable the 3-dimensional angle between the boresight of the receiver units and the line from the receiver units to the transmitters to be measured. This gives the pointing angle of the headset in space relative to the transmitter units 10, 12.

In order to determine the position of the headset in space relative to the console the 3-dimensional angle between the bore sight of each receiver unit and the line from the receiver unit to the transmitters needs to be obtained. To do this, the 14 bit numbers referred to above are processed in a similar manner to that described above but instead of the numbers being added vertically with reference to Figure 19 they are added horizontally for each photodetector A to L. Looking firstly at photodetector A, again, if the 14 bit digit $N_{AL1}=0$ then the signals received by photodetector A from the transmissions L1, L2 and L3 are ignored.

If we assume, as described above, N_{AL1} and N_{BL2} are both below the threshold then the signals from photodetectors A and B for the transmissions L1, L2 and L3 are ignored. Assuming, therefore, that each signal received by the photodetectors C to F for each of the transmissions L1 to L3 is above the threshold then the signals for transmission L1 received by the photodetectors C to F are summed to give a first summed signal $\Sigma L1_{C-F}$. This is repeated for the transmissions L2 and L3 to give summed signals $\Sigma L2_{C-F}$ and $\Sigma L3_{C-F}$. These signals are summed to provide a total summed signal ΣL_{1-3} and the ratios of the individual summed signals to the total summed signal are then processed to provide the 3-dimensional angle between the boresight of each transmitter unit and the line from the transmitter unit to each receiver unit. Thus, the position and orientation of the headset in space relative to the transmitter units 10,12 can be determined.

Since each triplet, whether it is a triplet of photodetectors of LED's, can only operate over a limited field of view, typically 75° to 80° it is necessary to use several triplets to achieve

the required field of view for the system. In the azimuth direction a field of view in excess of 200° is needed and it is for this reason that two receiver units 50, 52 are mounted on the headset 40 as shown in Figure 13 which is a plan view of the two receiver units 50, 52 on the headset 40. Looking at the left hand receiver unit 52, since the side faces 54 and 64 are parallel the azimuth field of view "seen" by the triplet ABD, subtends an angle α_1 of 80°. Equally, the triplet FBD also subtends an angle α_2 of 80°. This means that there is a narrow horizontal region between these two triplets (and also between triplets ACE and CEF) which is not covered. However, since two such receiver units are provided on the headset at an angle of 135° to one another, as previously described, there is a degree of overlap. Figure 20 shows the angles α_1 and α_2 with the corresponding angles α_3 and α_4 of the right hand receiver unit superimposed. Angles α_1 and α_3 overlap by at least 25° and preferably 35°, as do angles α_3 and α_2 and angles α_2 and α_4. Together, the receiver units provide an azimuth field of view of 215° with a 35° overlap.

For elevation, the field of view need not be as great and a field of view of 80° is sufficient. This is provided by overlap of the elevational field of view of two triplets on each receiver unit.

Claims

1. A system for determining the relative positions of first and second objects in space in the azimuth and vertical directions wherein one of said objects is stationary and the other of said object is moveable in space, the system comprising:

transmitter means on said first object for generating a radiation beam;

receiver means on said second object for receiving radiation transmitted by said transmitter means;

wherein either:

a) said transmitter means comprises three transmitters in a fixed, spaced relationship to one another for generating respective radiation beams; or

b) said receiver means comprises three receivers in a fixed, spaced relationship to one another for detecting said radiation;

and wherein the or each said receiver has a plane of sensitivity such that the intensity of incident radiation is proportional to the cosine of the angle of incidence of said radiation;

the system further comprising:

means for monitoring said intensity of the radiation incident at the or each said receiver from the or each transmitter and generating a respective direction cosine signal proportional to said intensity;

and micro processor means operable to determine from said signals a pointing vector of said moveable body from said stationary body.

2. A system as claimed in claim 1, further comprising two said receiver means in fixed, spaced relationship to one another;

wherein each said receiver means comprises three said receivers in fixed, spaced relationship to one another;

said monitoring means is operable to generate a respective direction cosine signal for the radiation incident at each said receiver from the or each said transmitter;

and said micro processor means is operable to determine from said direction cosine signals both said pointing vector and a head-up vector of said moveable body, and thereby determine the orientation of said moveable body relative to said stationary body.

3. A system as claimed in claim 2, wherein said transmitter means comprises three said transmitters in a fixed, spaced relationship to one another;

said monitoring means is operable to generate a respective direction cosine signal for the radiation incident at each said receiver from each said transmitter;

and said micro processor means is operable to determine from said direction cosine signals the position and orientation of said moveable body relative to said stationary body.

4. A system as claimed in claim 1, further comprising two said transmitter means in fixed, spaced relationship to one another;

wherein each said transmitter means comprises three said transmitters in fixed spaced relationship to one another;

said monitoring means is operable to generate a respective direction cosine signal for the radiation incident at the or each said receiver from each said transmitter;

and said micro processor means is operable to determine from said direction cosine signals both said pointing vector and a head-up vector of said moveable body, and thereby determine the orientation of said moveable body relative to said fixed body.

5. A system as claimed in claim 4, wherein said receiver means comprises three said receivers in a fixed, spaced relationship to one another for detecting said radiation;

said monitoring means is operable to generate a respective direction cosine signal for the radiation incident at each said receiver from each said transmitter;

and said micro processor means is operable to determine from said direction cosine signals the position and orientation of said moveable body relative to said stationary body.

6. A system as claimed in any preceding claim wherein, in said transmitter means having three said transmitters, said transmitters are arranged with their axes of radiation orthogonal.

7. A system as claimed in the preceding claim wherein, in said receivers means having three said receivers, said receivers are arranged with their planes of sensitivity orthogonal.

8. A system as claimed in any preceding claim wherein the or each said receiver means comprises six said receivers arranged in four orthogonal sets of three.

9. A system as claimed in any preceding claim, having two said receiver means positioned on said moveable body relative to one another to provide an azimuth field of view of at least 200°.

10. A system as claimed in any preceding claim having a single said transmitter and a plurality of said receivers wherein said micro processor means is operable to energise said transmitter for a pre-selected first time period and to monitor sequentially each said receiver during said time period thereby to obtain said direction cosine signals for each said receiver.

11. A system as claimed in any of claims 1 to 10 having a plurality of transmitters and a single receiver wherein said micro processor means is operable to energise said transmitters sequentially for a pre-selected time period and to monitor said receiver thereby to obtain said direction cosine signals for the radiation received by said receiver from each said transmitter.

12. A system as claimed in any of claims 1 to 10 having a plurality of said transmitters and a plurality of said receivers wherein said micro processor means is operable to monitor sequentially each said receiver for a pre-selected time period and to energise sequentially said transmitters during said time period thereby to obtain said direction cosine signals for radiation received by each receiver from each transmitter.

13. A system as claimed in any preceding claim wherein said radiation is pulsed infra-red radiation.

14. A method of determining the relative positions of first and second objects in space in the azimuth and vertical directions wherein one of said objects is stationary and the other of said object is moveable in space, the method comprising:

providing transmitter means on said first object for generating a radiation beam;

providing receiver means on said second object for receiving radiation transmitted by said transmitter means;

wherein either:

a) said transmitter means comprises three transmitters in a fixed, spaced relationship to one another for generating respective radiation beams; or

b) said receiver means comprises three receivers in a fixed, spaced relationship to one another for detecting said radiation;

and wherein the or each said receiver has a plane of sensitivity such that the intensity of incident radiation is proportional to the cosine of the angle of incidence of said radiation;

the method further comprising:

monitoring said intensity of the radiation incident at the or each said receiver from the or each transmitter and generating a respective direction cosine signal proportional to said intensity;

and determining from said signals a pointing vector of said moveable body from said stationary body.

15. A method as claimed in claim 14, further comprising providing two said receiver means in fixed, spaced relationship to one another;

wherein each said receiver means comprises three said receivers in fixed, spaced relationship to one another;

and wherein the method comprises:

monitoring said intensity of the radiation incident at each said receiver from the or each transmitter and generating a respective direction cosine signal for the radiation incident at each said receiver from the or each said transmitter;

and determining from said direction cosine signals both said pointing vector and a head-up vector of said moveable body, and thereby determine the orientation of said moveable body relative to said stationary body.

16. A method as claimed in claim 15, wherein said transmitter means comprises three said transmitters in a fixed, spaced relationship to one another;

the method comprising:

generating a respective direction cosine signal for the radiation incident at each said receiver from each said transmitter;

and determining from said direction cosine signals the position and orientation of said moveable body relative to said stationary body.

17. A method as claimed in claim 14, comprising providing two said transmitter means in fixed, spaced relationship to one another, wherein each said transmitter means comprises three said transmitters in fixed spaced relationship to one another;

generating a respective direction cosine signal for the radiation incident at the or each said receiver from each said transmitter;

and determining from said direction cosine signals both said pointing vector and a head-up vector of said moveable body, and thereby determine the orientation of said moveable body relative to said fixed body.

18. A method as claimed in claim 17, wherein said receiver means comprises three said receivers in a fixed, spaced relationship to one another for detecting said radiation;

and wherein the method comprises:

generating a respective direction cosine signal for the radiation incident at each said receiver from each said transmitter;

and determining from said direction cosine signals the position and orientation of said moveable body relative to said stationary body.

19. A method as claimed in any of claims 14 to 18 wherein, in said transmitter means

having three said transmitters, said transmitters are arranged with their axes of radiation orthogonal.

20. A method as claimed in any of claims 14 to 19 wherein, in said receivers means having three said receivers, said receivers are arranged with their planes of sensitivity orthogonal.

21. A method as claimed in any any of claims 14 to 20 wherein the or each said receiver means comprises six said receivers arranged in four orthogonal sets of three.

22. A method as claimed in any of claims 14 to 21 having two said transmitter means positioned on said moveable body relative to one another to provide an azimuth field of view of at least 200°.

23. A method as claimed in any of claims 14 to 22 having a single said transmitter and a plurality of said receivers, the method comprising:

energising said transmitter for a pre-selected first time period and monitoring sequentially each said receiver during said time period thereby to obtain said direction cosine signals for each said receiver.

24. A method as claimed in any of claims 14 to 22 having a plurality of transmitters and a single receiver, the method comprising energising said transmitters sequentially for a pre-selected time period and monitoring said receiver thereby to obtain said direction cosine signals for the radiation received by said receiver from each said transmitter.

25. A method as claimed in any of claims 14 to 22 having a plurality of said transmitters and a plurality of said receivers, the method comprising monitoring sequentially each said receiver for a pre-selected time period and energising sequentially said transmitters during said time period thereby to obtain said direction cosine signals for radiation received by each receiver from each transmitter.

26. A method as claimed in any of claims 14 to 25 wherein said radiation is pulsed infra-red radiation.

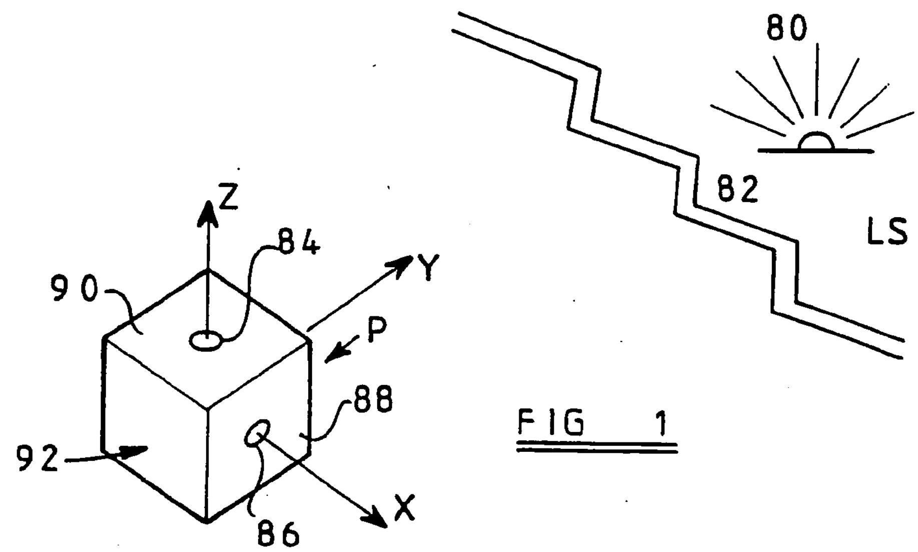


FIG 1

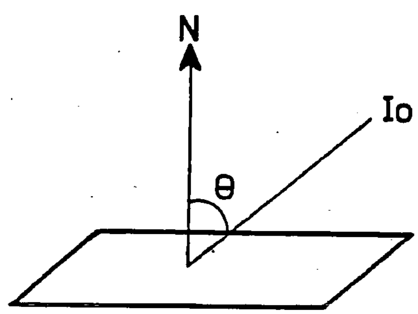
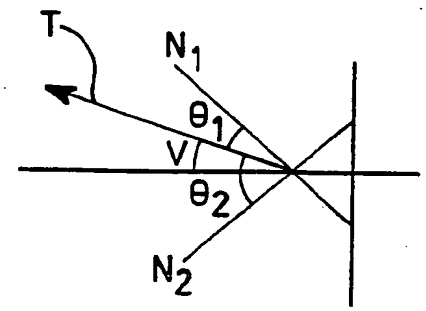


FIG 2



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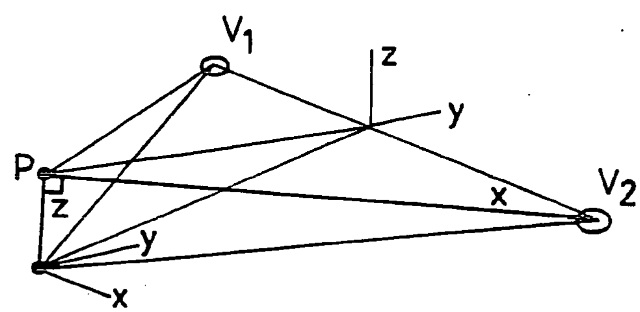


FIG 4

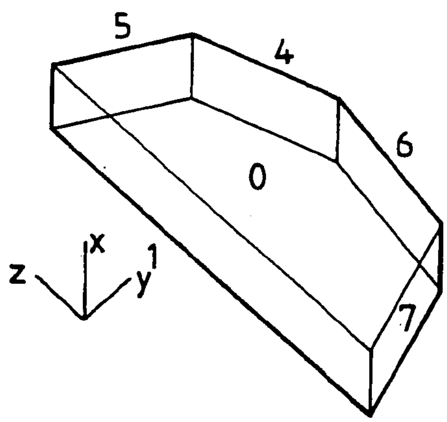
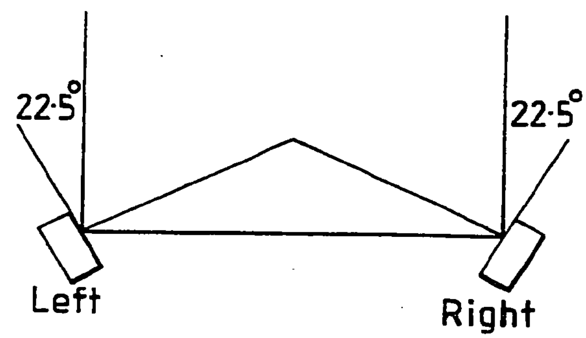


FIG 5

FIG 6



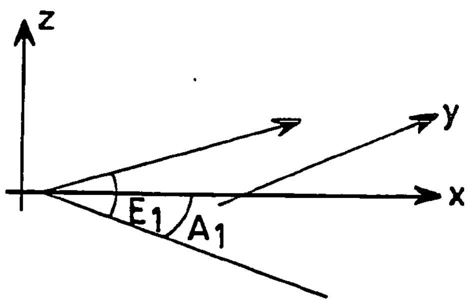


FIG 7a

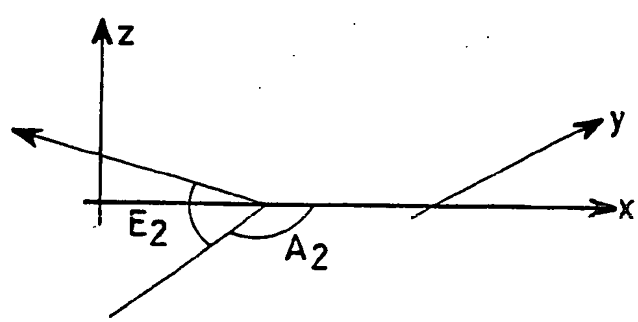


FIG 7b

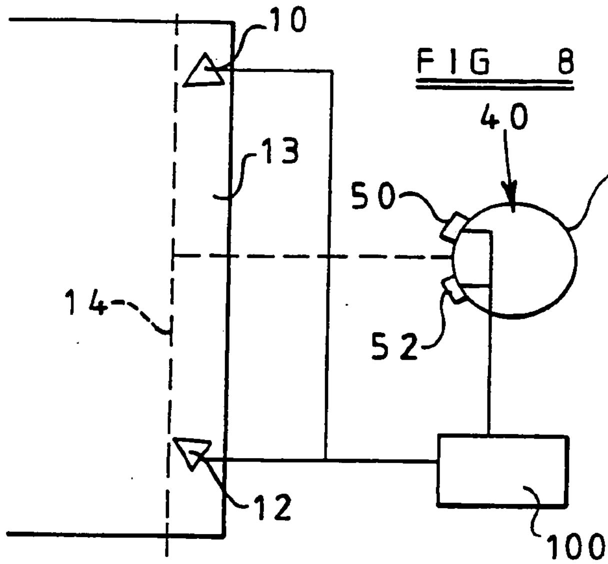


FIG 8

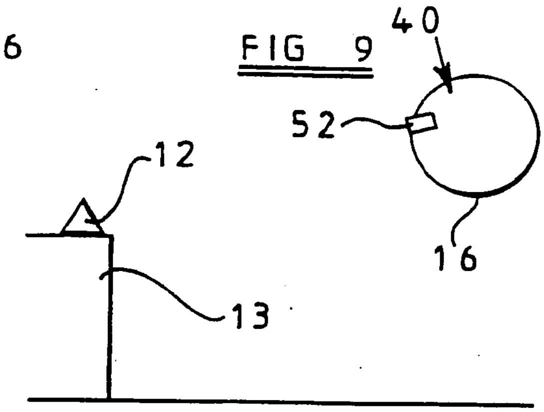


FIG 9

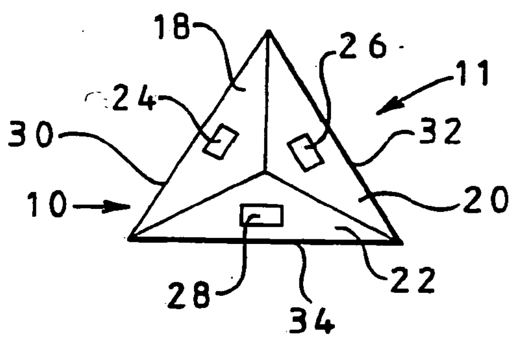


FIG 10

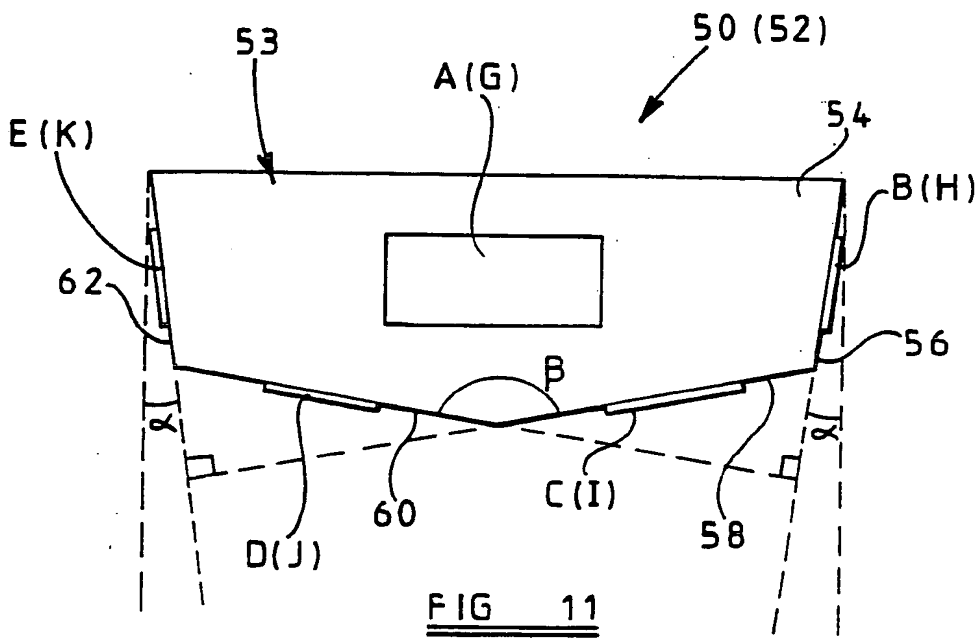


FIG 11

FIG 12

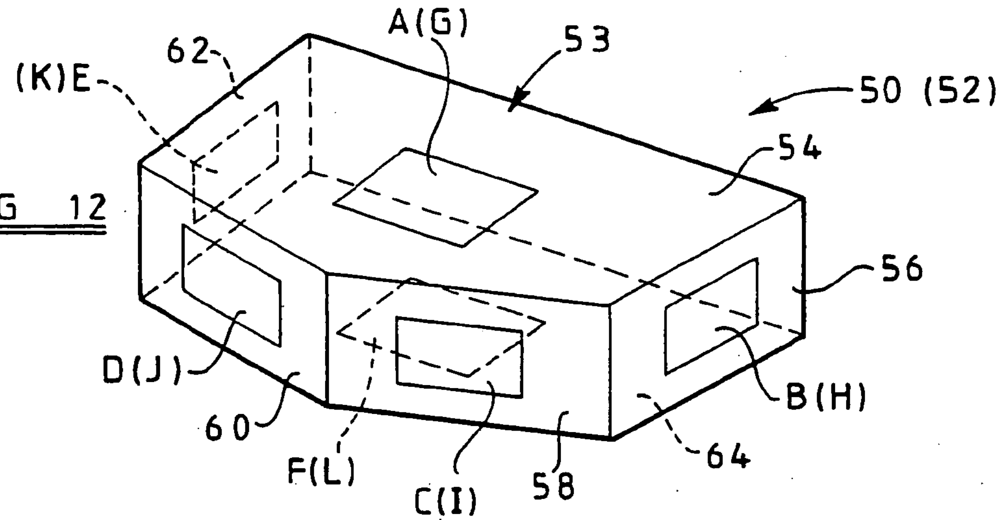


FIG 13

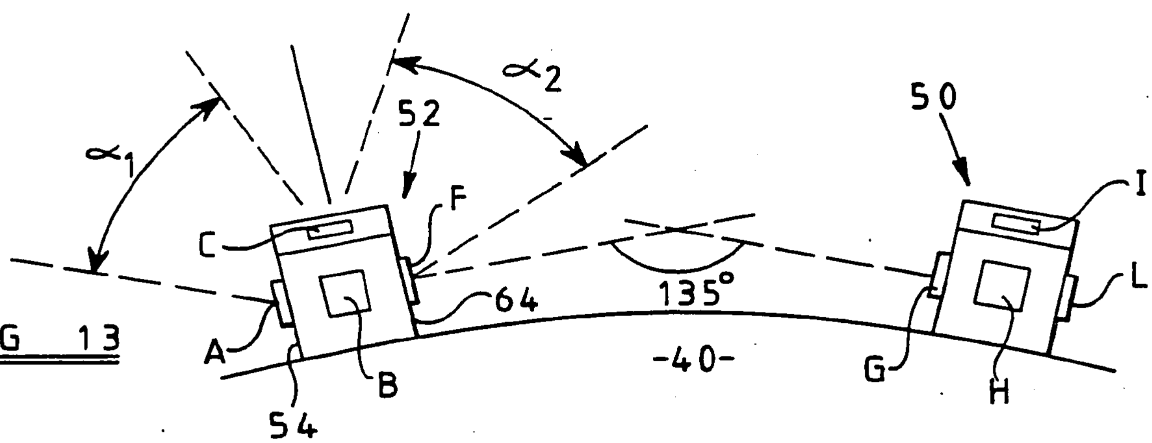
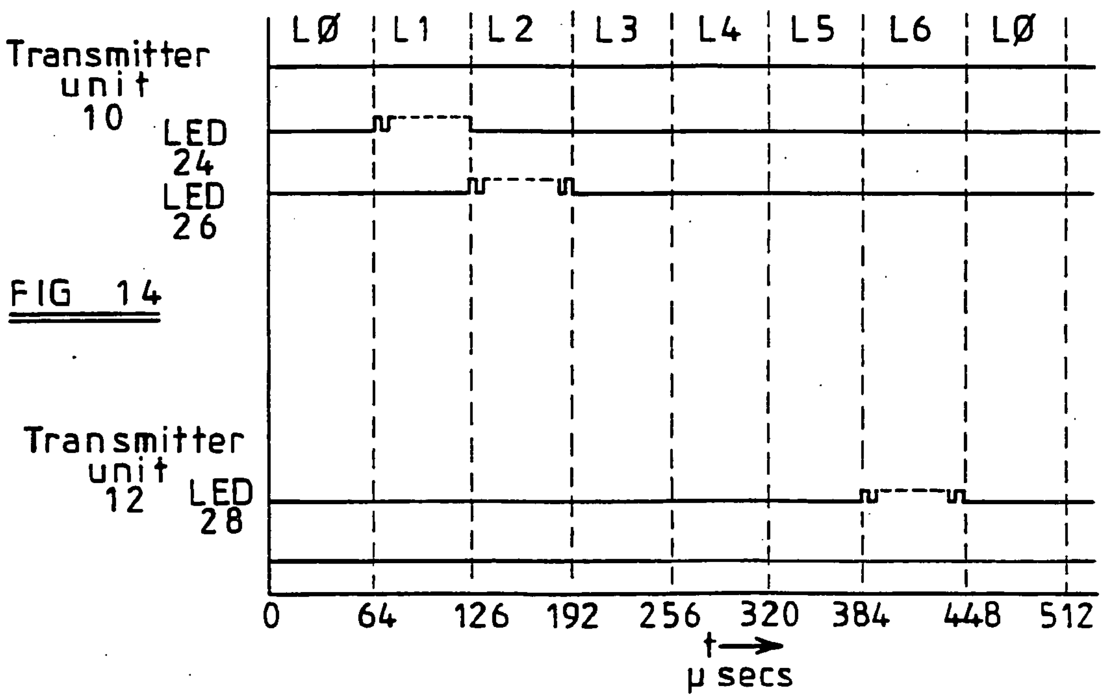


FIG 14



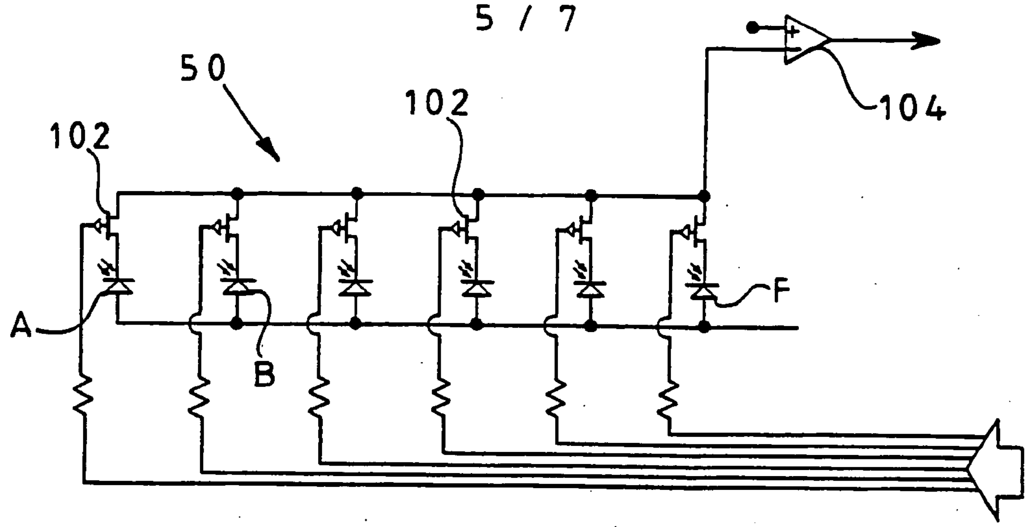
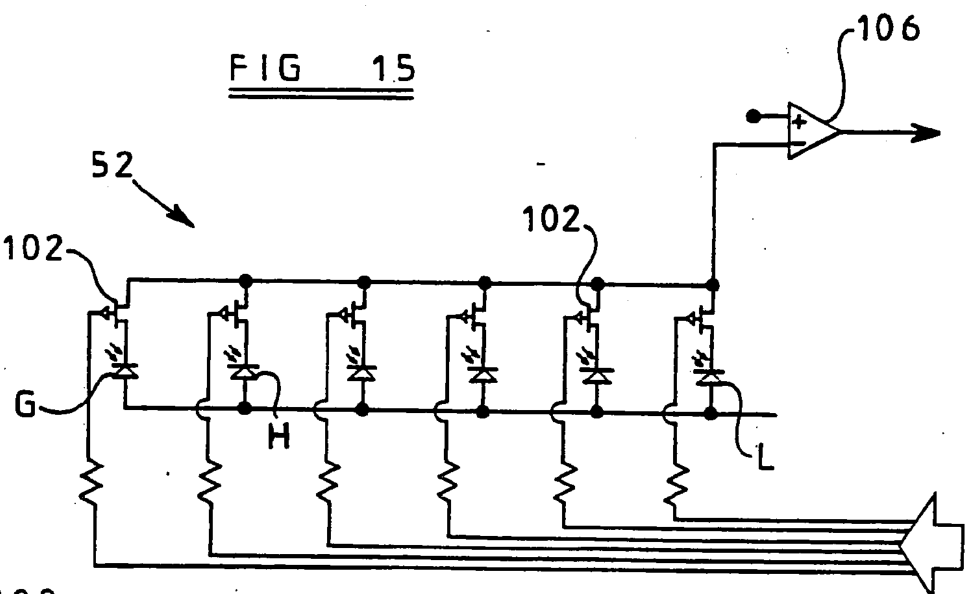

50
102
102
104
A
B
F

FIG 15


106
52
102
102
G
H
L

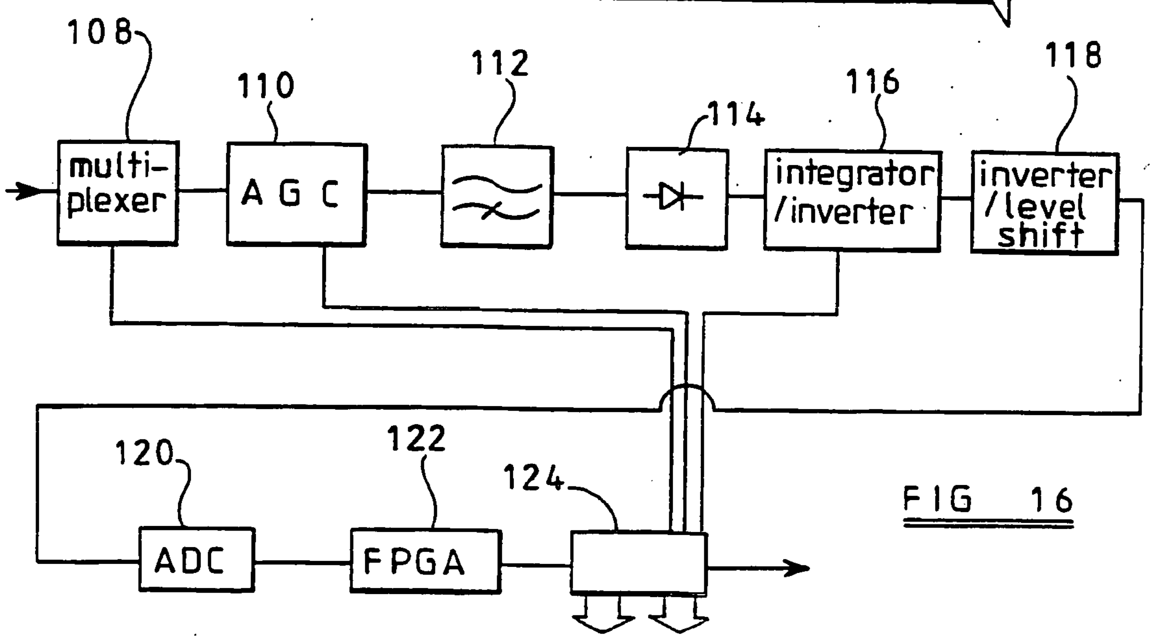

108
110
112
114
116
118
multi-
plexer
A G C
integrator
/inverter
inverter
/level
shift
120
122
124
ADC
FPGA

FIG 16

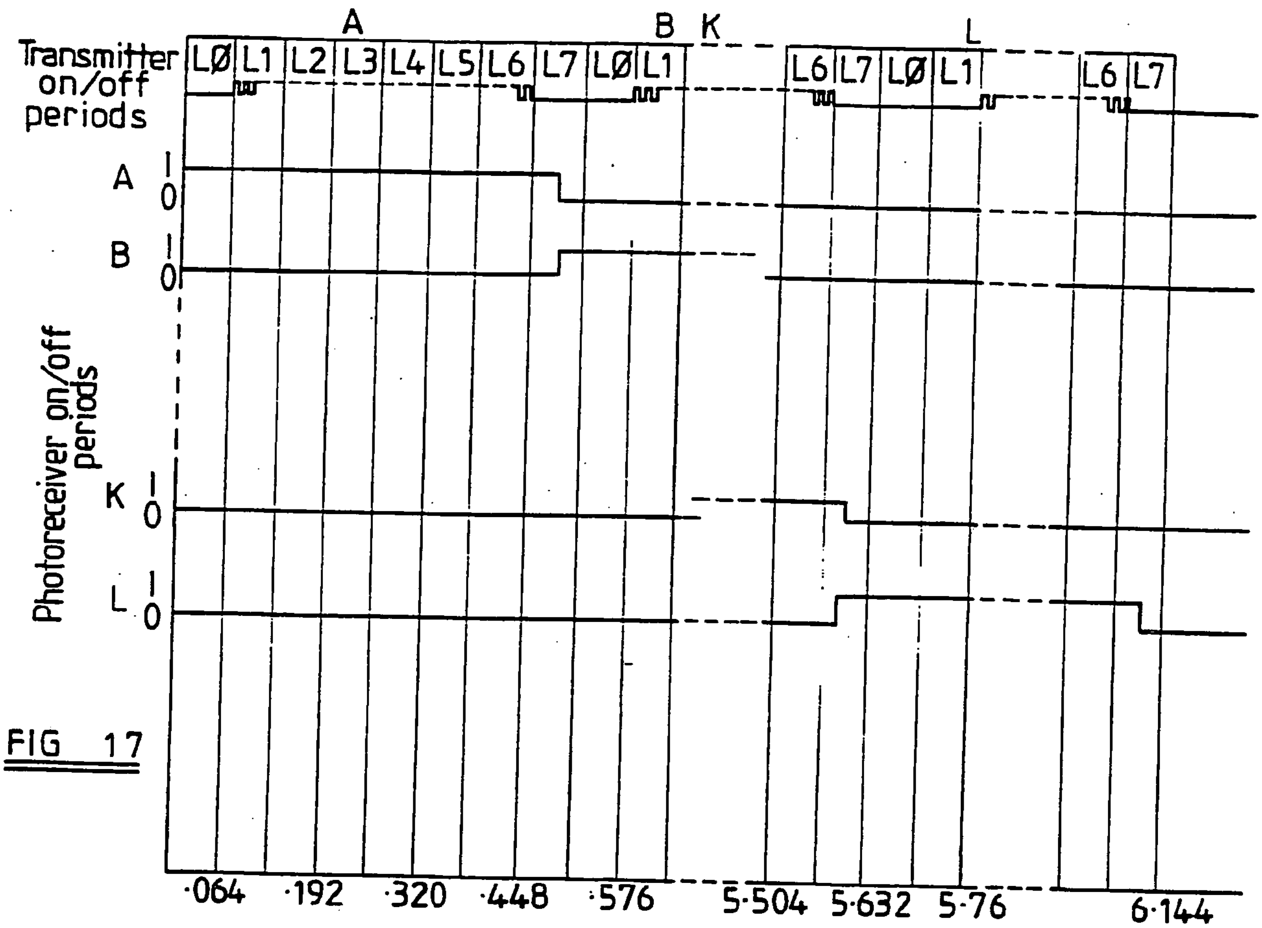
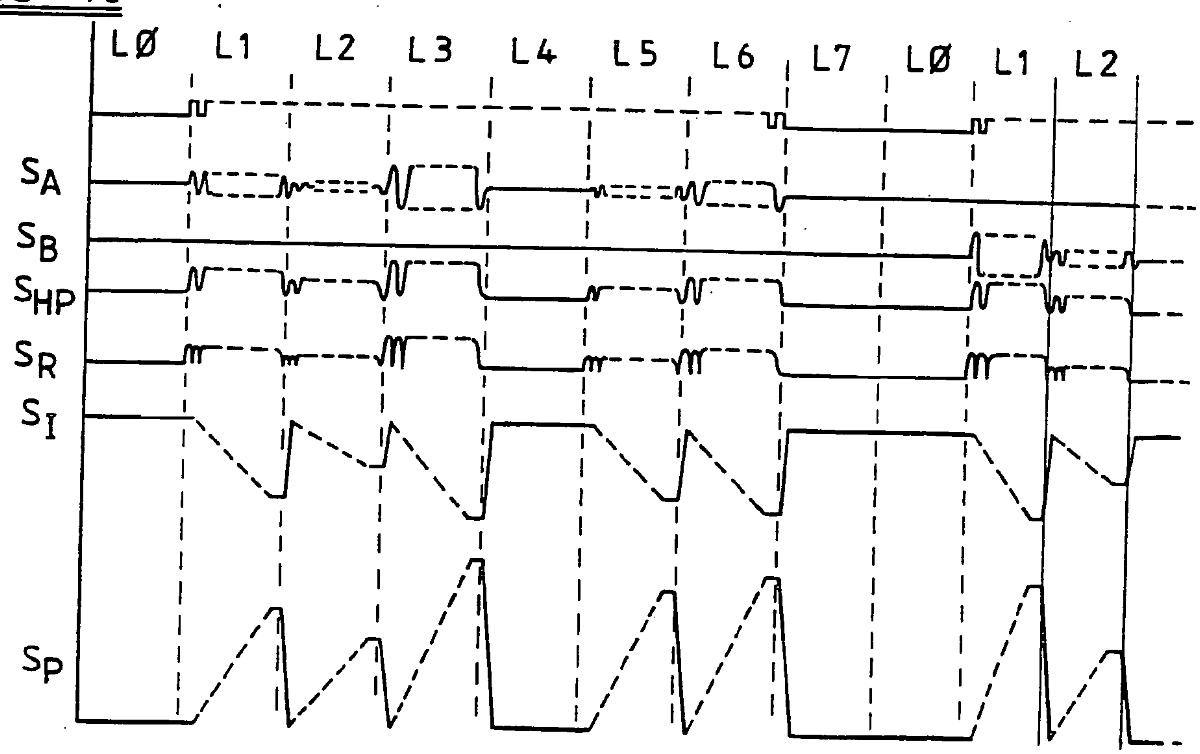

A
B
K
L
Transmitter on/off periods
LØ
L1
L2
L3
L4
L5
L6
L7
LØ
L1
L6
L7
LØ
L1
L6
L7
A
B
Photoreceiver on/off periods
K
L
1
0
·064
·192
·320
·448
·576
5·504
5·632
5·76
6·144

FIG 17

FIG 18


LØ
L1
L2
L3
L4
L5
L6
L7
LØ
L1
L2
S_A
S_B
S_{HP}
S_R
S_I
S_P

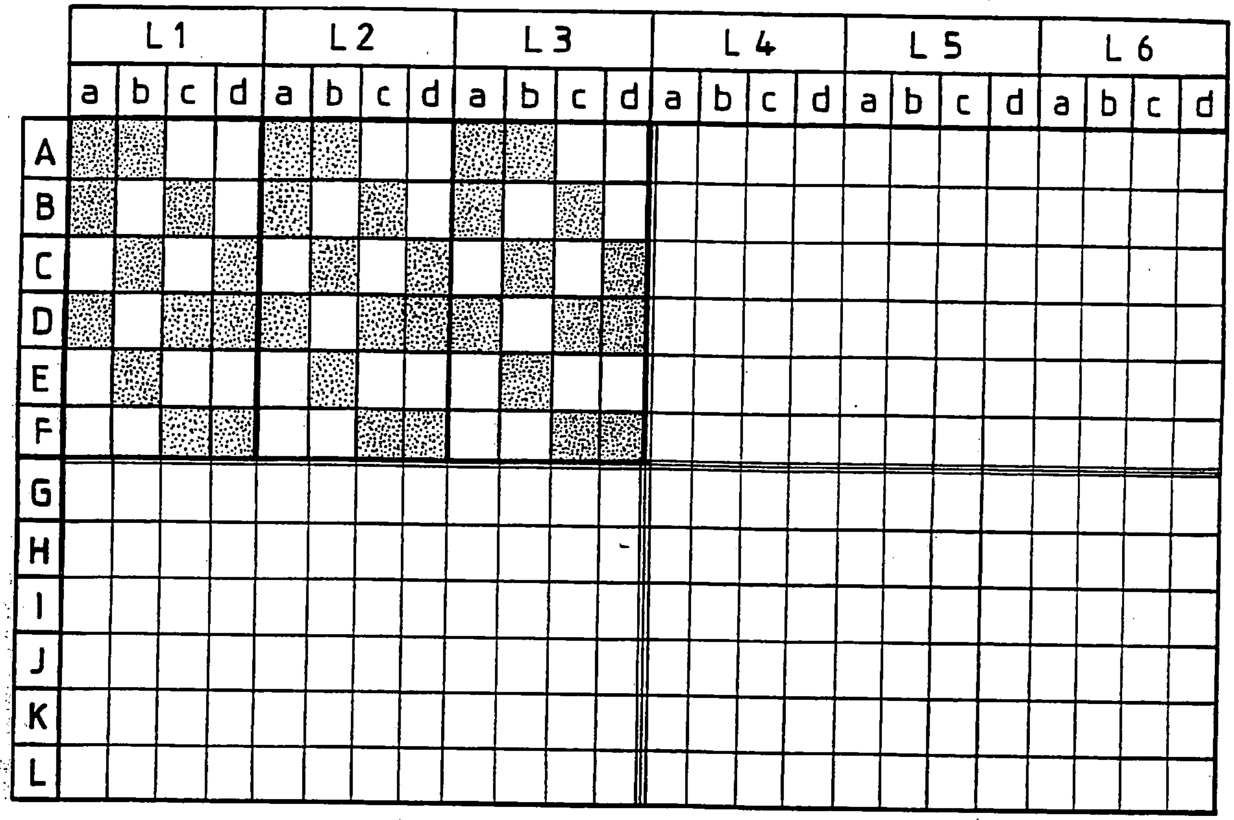

L1
L2
L3
L4
L5
L6
a b c d a b c d a b c d a b c d a b c d a b c d
A
B
C
D
E
F
G
H
I
J
K
L

FIG 19

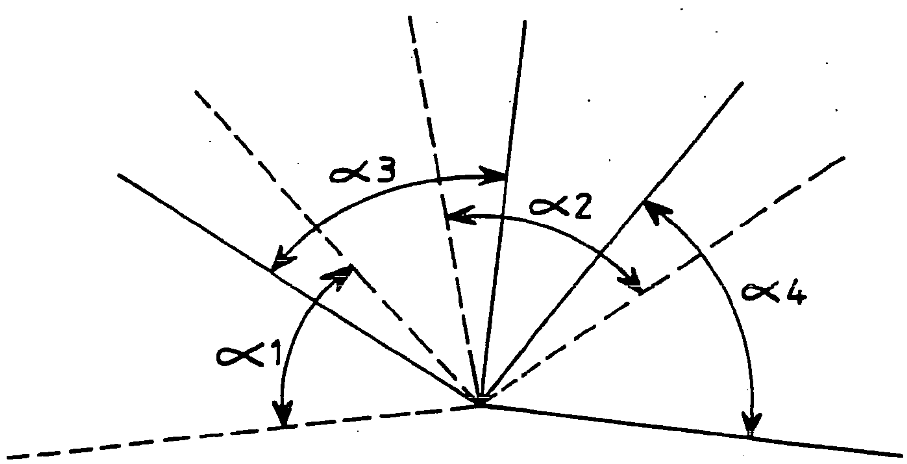

∝3
∝2
∝1
∝4

FIG 20

INTERNATIONAL SEARCH REPORT

Inten. nal Application No
PCT/GB 96/01141

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01S5/16 G01S5/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	WO,A,95 19577 (MIKTO LTD ;GILBERT ROGER MARK ANTHONY (GB); WEINREICH JONATHAN (GB)) 20 July 1995 see page 8, line 23 - page 13, line 15	1-9, 13-22,26
Y,P		10-12, 23-25
Y	EP,A,0 620 448 (POLHEMUS INC) 19 October 1994 see page 3, line 41 - page 4, line 43	10-12, 23-25
X	US,A,4 742 356 (KUIPERS JACK) 3 May 1988 see column 1, line 42 - column 2, line 2 see column 2, line 38 - column 2, line 49 see column 3, line 21 - column 3, line 42 see column 5 - column 6	1-25

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

2

Date of the actual completion of the international search	Date of mailing of the international search report
1 August 1996	03.09.96

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	McLean, G

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INTERNATIONAL SEARCH REPORT

Inter. ›nal Application No
PCT/GB 96/01141

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A,3 678 283 (LABAW KENNETH B) 18 July 1972 -----	1-25

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter. ɔnal Application No
PCT/GB 96/01141

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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EP-A-0620448	19-10-94	US-A- 5453686	26-09-95
		CA-A- 2120819	09-10-94
		JP-A- 6347527	22-12-94
US-A-4742356	03-05-88	NONE	
US-A-3678283	18-07-72	NONE	